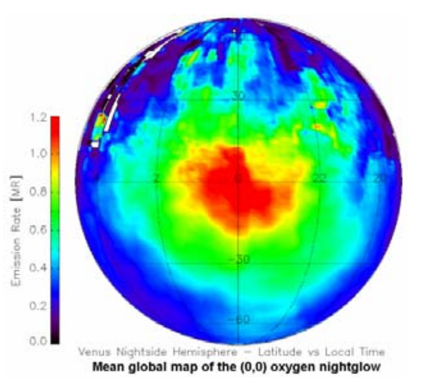

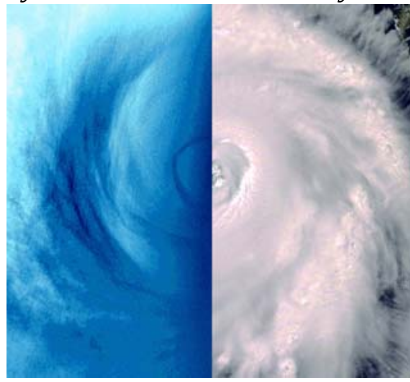

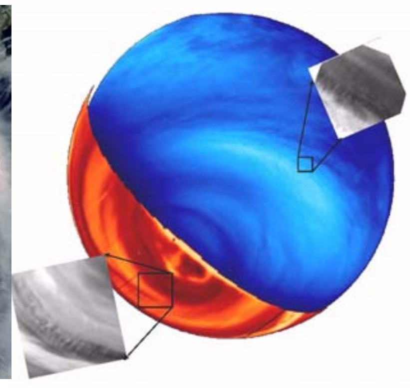

Venus Atmosphere: Major Questions and Required Observations

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See Appendix for Additonal endorsements received via the VEXAG web site

14 September 2009

Executive Summary

"How Does Venus atmosphere work?" A dedicated and renewed exploration effort is required to address this fundamental question. Key questions requiring new observations include: How did Venus' atmospheric runaway greenhouse evolve? What drives Venus' atmospheric super-rotation? What is the dynamical structure of the atmosphere from the surface to the thermosphere? How does the Venus atmosphere maintain its compositional stability? How do the surface and atmosphere interact to affect their respective compositions? How are the clouds formed and maintained? How is sunlight absorbed in the Venus atmosphere? What atmospheric loss mechanisms are currently at work? Did Venus ever have oceans, and if so, for how long? Did Venus' early atmosphere experience catastrophic loss, either due to hydrodynamic escape or a large impact? Why has Venus' climate deviated so dramatically from that of the Earth? Is Venus volcanically active? By studying Venus, we can learn more about the stability of the Earth's climate system, and most importantly, better educate the public about climate change on Earth by improving our understanding of the evolution of Venus' climate.

Venus exhibits a very dynamic atmosphere, showing changes on different time scales. To understand its structure, and variability and to learn about its evolution, multispectral imaging or mapping with adequate spatial and temporal resolution from properly chosen orbits, atmospheric wind and structure observations from long lived balloons, entry probes and long-lived landed platforms are required to provide new data essential to answer the fundamental atmospheric questions.

Magellan was the last dedicated US mission to explore Venus in the 1980's. More recently, ESA's Venus Express (VEX) orbiter has observed Venus since April 2006. VEX, in particular has provided key measurements and observed new dynamical phenomena requiring follow-on exploration missions to acquire additional data in greater detail and coverage. Japan's planned launch of the Venus Climate Orbiter in May 2010 to study the Venus cloud dynamics is one step in this direction.

A variety of missions are being considered that include balloons, probes, landers and orbiters and such missions have previously been proposed or are currently being proposed to NASA's Discovery and New Frontiers programs and are also part of NASA's Venus flagship mission (Bullock et al. 2009). The successful execution of these mission concepts promises to deliver needed fundamental data and insights into how Venus works dynamically, chemically, and meteorologically, and how its presently inhospitable environment came to be.

1. Introduction

Crisp et al. (2002) identified a number of major questions regarding Venus as part of the community input for the first Planetary Science Decadal Survey. Subsequently, the European Space Agency's Venus Express Orbiter has been monitoring the planet since 2006 from an eccentric polar orbit and has provided new information about Venus, including revelations about the structure as well as longitudinal and temporal variability of the zonal winds, the latitudinal variability of key chemical constituents, and the gross distribution of granitic and basaltic rocks across the south polar region. The S-shaped feature (also previously called the "dipole") over the planet's north pole discovered by Pioneer Venus in 1979, has now also been observed by Venus Express around the south pole (Piccioni et al., 2007). These and other polar features have been attributed to dynamical instability found in the central region of vortices, caused by latitudinal wind shear. Evolving over time, these instability features assume different shapes depending on the shear and are analogous to those found in tropical cyclones (Limaye et al., 2009). Yet little is known about their vertical circulation, temporal evolution, and role in the maintenance of the super-rotation.

Venus Express and Venus Climate Orbiter (VCO) are capable of providing a wealth of new data that will enable us to address key Venus science questions. However, their data sets are limited by two important factors. The first is that each orbital mission focuses on a limited geographical area due to its orbit – the southern polar regions for Venus

Express, and equatorial regions for VCO – which makes it difficult to build global maps of many phenomena, including winds, waves, and chemical abundances. The second, more fundamental limitation is that remote sensing observations provide very little information about the atmosphere below the Venus cloud-tops. Near-IR window regions allow mapping on the nightside of Venus of several chemicals at 30-45 km altitude, using the 2.2-2.6 μm band (CO, OCS, H_2O and others) and H_2O mapping at lower altitudes (0-15 km and 15-30 km) using the 1.18 and 1.74 μm windows. The information obtained on the atmospheric chemistry in the lower atmosphere is thus very limited, particularly in the vertical and temporal dimensions. Venus Express imagery has revealed a vast diversity of cloud types, morphologies and wave patterns; however, it will capture neither the vertical structure of the cloud deck, nor the chemical composition of much of the cloud, nor the processes giving rise to the observed morphology.

The questions identified by Crisp et al. (2002) are still largely unanswered. Beginning in December 2010 the Japanese Venus Climate Orbiter (VCO) is also expected to provide new measurements of the global atmospheric circulation at the cloud top level (day side) and near the cloud bottom (night side). Yet, some key required measurements will still be lacking. To help answer the fundamental question "How Venus Works", NASA appointed the Venus Science and Technology Definition Team (VSTDT) in 2009 to perform a study for a "Flagship" mission (Bullock et al., 2009). This mission concept can be refined pending any precursor New Frontiers and Discovery missions to Venus. Here we expand upon the previous findings and emphasize the investigations needed for a better understanding of the Venus atmosphere.

2. Atmospheric Evolution and Composition

The divergent evolution of the Venus atmosphere as compared to Earth's atmosphere is key to understanding the evolution of terrestrial planets in general, including Earth-like planets around other stars. To achieve this understanding, we need to know the original makeup of Venus including the processes that led to the formation and early evolution of the planet. For example, is the current Venus atmosphere a secondary atmosphere – as it is on Earth and Mars – or is the atmosphere essentially the original? If it is a secondary atmosphere, is it largely due to late comet or planetesimal bombardment which disrupted the original atmosphere and also introduced significant outer-solar system materials, including volatiles, to the planet? Was the environment of Venus similar to the Earth in its early history? For example, did it have oceans and does it have current significant volcanic activity?

To answer such questions, tracers of Venus' past history must be sought and measured, including, in particular, noble gases and their isotopes. In particular, the heaviest noble gases – xenon and krypton – need to be accurately measured (Baines et al., 2007). No measurements of bulk xenon or of its nine tell-tale isotopes that can inform about the evolution have been obtained, and measurements of krypton abundances vary by over an order of magnitude. The history of water on Venus is another key question. Venus Express has yielded intriguing new remote sensing measurements of the D/H ratio in the upper atmosphere above the clouds, revealing that D/H is much higher (~ 240 times the terrestrial value) than in the deep atmosphere (~ 150). This may indicate shorter timescales for the loss of water from the top of the atmosphere than previously thought. New analyses of infrared imaging from Galileo NIMS (Hashimoto et al., 2009) and VEX/VIRTIS (Mueller et al., 2008) both indicate marked emissivity differences between lowlands, thought to be basaltic volcanic plains, and highlands, which are considered to represent ancient terrain. The lower 1μm emissivity found in highland regions suggests the presence of felsic rocks such as anorthosite, as found in lunar highlands, or granite, as found on Earth. The formation of granites on Earth requires large amounts of liquid water, very significant for our understanding of the evolution of Venus' climate. What caused Venus to evolve to such a dry state that sulfur chemistry dominates is thus a fundamental area of inquiry.

Another result from Venus Express that needs further exploration is the discovery that Venus is chemically "alive," with constituents that vary spatially and temporally. A key finding from Venus Express by VIRTIS is the discovery of the hydroxyl molecule in the upper atmosphere (Piccioni et al., 2008). The amount of hydroxyl at Venus varies widely, changing by as much as 50% from one orbit to the next; which may be caused by uneven distribution of ozone in the atmosphere. Photochemical model calculations suggest that the observed OH emission is produced primarily via the Bates-Nicolet mechanism, as on the Earth. The sulfuric acid particles that are known to dominate the composition of the clouds of Venus are generated photochemically from SO_2 and OCS in the upper Venus atmosphere. However, the photochemical processes likely also involve chlorine, which has long been detected in the Venus atmosphere. Processes not unlike those observed in the Earth's stratosphere have been postulated to occur on Venus (DeMore and Yung 1982), but key trace species in these processes have not been observed in the Venus middle atmosphere. These photochemical processes must also stabilize Venus' atmosphere where various catalytic cycles or heterogeneous processes convert the photo-dissociated products of CO_2, CO and O_2, back to CO_2.

Furthermore, the production of species such as hydrochloric acid can have additional effects on the microphysical behavior of the Venus clouds, specifically, in the role of water and the hydration state of the acids. The distribution of SO_2 produced from thermochemically generated H_2S and OCS is intimately related to the behavior of not only the sulfuric acid condensate, but also the dynamics of the upper atmosphere. It is important to understand the relative role of dynamics and cloud microphysics in the distribution of the sulfur and halogen species.

3. Atmospheric Dynamics

The super-rotation of the Venus atmosphere remains a puzzle. While the main aspects of the Venus atmospheric circulation have been measured since the discovery of the super-rotation at the cloud level (~ 70 km altitude at low latitudes and ~ 67 km at high latitudes) and confirmed by entry probes to extend down to the surface, key aspects of the three dimensional structure of the global circulation on Venus have not yet been measured. One of these aspects is knowledge of zonal winds at a constant altitude around the globe in particular, in both the day and night hemispheres. As a consequence, the solar thermal tidal structure has not been adequately determined. Thus, the role of thermal tides in powering the planet's super-rotation is unknown. Prospects for obtaining solar tides from currently funded orbital missions to Venus are limited by the inability to measure cloud motions at the same level at all longitudes. The following aspects have been observed (Limaye, 2007):

- Vertical profiles of the zonal and meridional components of the wind from ~ 62 km down to the surface by the four Pioneer Venus and many Venera entry probes (Gierasch et al., 1997). However, the local time coverage from these observations still has significant gaps due to insufficient sampling.
- Zonal, meridional and vertical wind components for ~ 48 hours for each of two VeGa balloons at ~ 55 km altitude (between 00h LST till 0700 LST) in 1983 (Sagdeyev et al., 1992), spanning 100 degrees of longitude on the planet's nightside.
- Latitudinal and longitudinal structure of the cloud tracked winds on the day-side during ~ 2.5 days of Mariner 10 observations, from Pioneer Venus Orbiter Cloud Photopolarimeter (1979 – 1983) observations, by Galileo Orbiter imaging observations (1990), and most recently from Venus Express (Moissl et al., 2009).
- Thermal structure from entry probes, radio occultation profiles from the Pioneer Venus Orbiter, Venera orbiters and Venus Express orbiter and from infrared observations (VEX/VIRTIS).
- Latitudinal profiles of the longitudinal average of some trace species abundance in a few layers (CO and SO_2) and O_2 and NO airglow maps on the night side that are markers of transport from

dayside to the nightside above 80 km altitude, in the transition between the superrotation (below 80 km) and the day-night circulation in the thermosphere (80-140 km).

Above the cloud tops (80 – 140 km) the Venus atmosphere shows two flow regimes – (i) a stable sub-solar to anti-solar point circulation driven by solar EUV heating, and (ii) a super-rotating zonal flow that varies greatly over time. Breaking gravity waves propagating from below have been observed and appear to dissipate in the 140-150 km region. While many ground-based studies have yielded line-of-sight Doppler wind velocities and are useful to determine spatial and temporal variations, such measurements have not led to a better understanding of the Venus circulation due to incomplete information, including: (1) the missing crucial orthogonal or meridional component, (2) the lack of temporal continuity, and (3) inadequate spatial coverage and resolution. Mid-latitude jets at the level where UV radiation is absorbed in the cloud layer (60 – 70 km) have been observed but not at all periods. While it is possible that the absence of a mid-latitude jet signifies vacillation of the global circulation (Del Genio and Rossow, 1990), changes in the supporting thermal structure have not been confirmed due to lack of concurrent thermal structure data. A likely possibility is that the absence of a jet is an artifact of a change in cloud morphology which provides far fewer discrete cloud features that can be tracked un-ambiguously. Aspects of the global atmospheric circulation critical for understanding global super-rotation that are not well known or <u>not known at all</u> include:

- Global longitudinal and latitudinal structure of the zonal and meridional flow at a known level over at least one Venus day
- Vertical structure of the horizontal flow, which is critical to understanding Hadley cell structure
- Amplitudes and phases of solar thermal tidal winds at any level
- Reliable estimates of zonal and time-averaged latitudinal profiles of the meridional transports of absolute angular momentum, heat and trace species at any level
- Exchange of angular momentum between the atmosphere and the solid planet over time
- Middle atmosphere circulation (70-140 km) at high spatial and temporal resolution
- Structure of planetary and small scale waves and their role in the atmospheric circulation
- Structure of waves in the thermosphere such as the nine day oscillation observed in the thermosphere (Forbes and Konopliv, 2007)

Future missions are needed to return data to improve understanding of Venus circulation.

4. The Ultraviolet Absorber and Venus Clouds

Besides the identity of the ultraviolet (UV) absorber, the next major question about the clouds is the high spatial inhomogeneity and rapid temporal variability. Why isn't the UV absorber well mixed? The answer may lie in sulfur chemistry, and high spatial and temporal resolution observations of temperature and of characteristics of cloud/aerosols and chemical species to understand the latitudinal and temporal behavior of the UV absorbers.

The nature of the UV absorber is still a mystery and the possible existence of large and/or crystalline cloud particles has not yet been confirmed (Esposito et al., 1997). It is important to monitor the allotropes of sulfur, which have been suggested as the possible UV absorber. Monitoring of the UV contrasts through imaging from Venus Express has shown a dynamic behavior that has been suggestive of convective connections in equatorial latitudes (Titov et al., 2009). At polar latitudes a correlation between dark streaks and warmer (deeper) brightness temperatures at infrared wavelengths has been discovered from concurrent observations from VMC and VIRTIS instruments on Venus Express (Ignatiev et al., 2009), but there are puzzling exceptions as well. It has not been established whether these high-latitude contrasts are due to increased absorber, an artifact of the scattering, or both. Data from Venus Express suggest that OCS is converted to CO in the lower atmosphere around 30 km by heterogeneous chemistry. The process may produce polysulfur, a

source of cloud top region UV absorber (Yung et al. 2009).

The lower cloud region is also poorly understood. Although it is likely to be composed primarily of sulfuric acid droplets, X-ray fluorescence data from the Soviet VeGa descent probes (Andreychikov, et al., 1987) found significant and spatially variable quantities of Cl, P, and Fe in the lower cloud particles, although it is not clear in what chemical form. It has not been possible to study this using remote sounding, so future *in situ* missions are required to investigate the complex cloud chemistry of the lower cloud deck.

Additionally, mechanisms responsible for the formation and dissipation of Venus's clouds have not been verified. For example, while a sulfur cycle involving a variety of sulfur-bearing molecules and water has been implicated, the correlation of these molecules and their daughter sulfuric cloud particles has not been measured. The nature of these photochemically produced aerosols can have significant effects on the makeup of the Venus clouds. For example, different compounds may have differing solubilities in sulfuric acid, which in the middle and lower clouds will lead to condensation of vapor onto these particles at different supersaturations. In the upper cloud, these different compounds might induce the supercooled sulfuric acid to freeze, changing its optical properties. Also, dynamical and chemical variations responsible for the spatial inhomogeneity of clouds have not been identified. In situ measurements by balloon-borne instrumentation floating for several days in the clouds should provide fundamental new information critical to clarify understanding of cloud meteorology.

5. Cloud Structure, Thermal Structure and Radiative Balance

Since the last Decadal Survey, Venus Express has provided some new information about the Venus cloud structure. Early results indicate spatial and temporal variability in cloud properties and suggest more convective activity in equatorial latitudes, consistent with the solar heating (Satoh et al., 2009; McGouldrick et al., 2009). A combined analysis of VMC UV images and VIRTIS data indicates that the UV cloud tops are at the ~ 70 km level in low latitudes and ~ 67 km in high latitudes (Ignatiev et al., 2009). Near-infrared observations in spectral windows into the Venus atmosphere indicate significant variability in Venus' middle and lower cloud decks. Although strong downdrafts have been implicated as the source of holes in the clouds, causes for these downdrafts remain elusive, and the coupling between the microphysics, radiative balance and atmospheric dynamics is incompletely known. Furthermore, clouds play an important radiative role in both the UV/visible and infrared spectral regions. Thus, variations of cloud cover in latitude or in local solar time can both drive or be driven by the dynamics.

One of the important measurements needed is the near surface vertical temperature structure at latitudes from equator to the poles which impacts convective activity. The VeGa 2 lander is the only probe that has been able to measure the temperature in the lowest 12 km of the atmosphere down to the surface; it indicated superadiabatic lapse rates. Confirmation of this superadiabatic layer is critical to a better understanding of the lower atmosphere and its impact on the deep atmosphere circulation via convection and maintenance of the thermal structure (Crisp and Titov, 1997). Of particular interest is the lower atmosphere thermal structure in polar latitudes.

6. Modeling Needs

Given the practical challenges of obtaining desired synoptic observations of the Venus atmosphere, capable numerical models are needed to improve our understanding of the past, current and possible future states of the atmosphere. The models need to capture the necessary physics accurately enough to represent the real atmosphere. This requires a good knowledge of topography, composition, cloud structure, and radiative properties of the atmosphere and surface. It would seem, for a planet with no significant seasons, lack of oceans, a hydrologic cycle, and uniform cloud cover, that the simulation of its circulation would be easy. However, this has not been the case, since three-dimensional general

circulation models (GCMs) of Venus must also confront the fact that the planet's massive atmosphere has a heat capacity several orders of magnitude greater than Earth's, which leads to practical computational difficulties. Recent Venus GCM development efforts have obtained strong greenhouse warming and atmospheric super-rotation that approximately resemble observations, but the models have not yet matched the "real Venus" (Lebonnois et al., 2009). Capable GCMs of the Venus atmosphere that can reproduce and assimilate the observed features of thermal structure, circulation, and eventually clouds and chemistry are essential for a proper understanding of "how the atmosphere works." The logical path forward is a more systematic diagnosis and intercomparison of Venus GCMs, as has been done for their Earth counterparts (e.g., Gates et al., 1998). An informal effort to compare the different numerical model simulations of the Venus atmosphere has been initiated (Bengtsson, 2008), but additional efforts are required not only in intercomparisons but in improving the resolution of the models and their treatment of radiation, clouds, and surface-atmosphere interaction.

7. Observation Strategies

Long-lived balloons, deep probes and orbiting spacecraft in properly-chosen circular orbits can each provide required measurements of winds, temperatures and abundances of diagnostic trace species that make the Venus atmosphere so dynamic. Each platform covers a unique piece of the full spatial/temporal domain. Complete and accurate longitudinal and time-of-day sampling of temperatures, trace species, and winds in all three dimensions are achievable with balloons floating at known altitudes. A large range of latitudes can be sampled as well, as balloons drift poleward over several weeks at suitable altitudes. A probe can give a single precise profile of temperatures, trace species, and zonal and meridional winds down to the surface at one location at one time. Orbiting spacecraft can map zonal and meridional winds at a specific cloud level by cloud tracking in images taken in reflected solar light images or thermal emission from the deep atmosphere. Spacecraft can also map trace species such as CO (diagnostic of atmospheric transports). Ultimately, a variety of measurement platforms are needed to achieve a complete picture of Venus. Ideally, multiple probes and landers at high latitudes, multiple balloons at a variety of altitudes, and multiple orbiters in circular orbits over a variety of inclinations can make up for the lack of synoptic observations of the atmosphere. For practical reasons, we have to rely on a blend of (1) asynchronous spatially-distributed and Lagrangian observations, and (2) numerical models, to understand the aspects of Venus atmospheric circulation. Due to their ability to precisely measure numerous atmospheric parameters over a wide range of longitudes and time, high-altitude (~ 55 km), long-lived balloons have become an essential component of many large and international missions, including the Venus Design Reference "Flagship" Mission (Bullock et al., 2009), Venera–D (Korablev et al. 2006) and the European Venus Explorer (Chassefiere et al., 2009) being proposed to ESA's Cosmic Vision program. Crisp et al. (2002) recommended an Atmospheric Dynamics Explorer and a Chemical Composition Orbiter to Venus as two of several missions needed to understand Venus. We recommend implementation and coordination of such international missions to Venus and those proposed to New Frontiers and Discovery programs. These missions will provide fundamental new insights and answers to the basic question, "How does Venus atmosphere work?"

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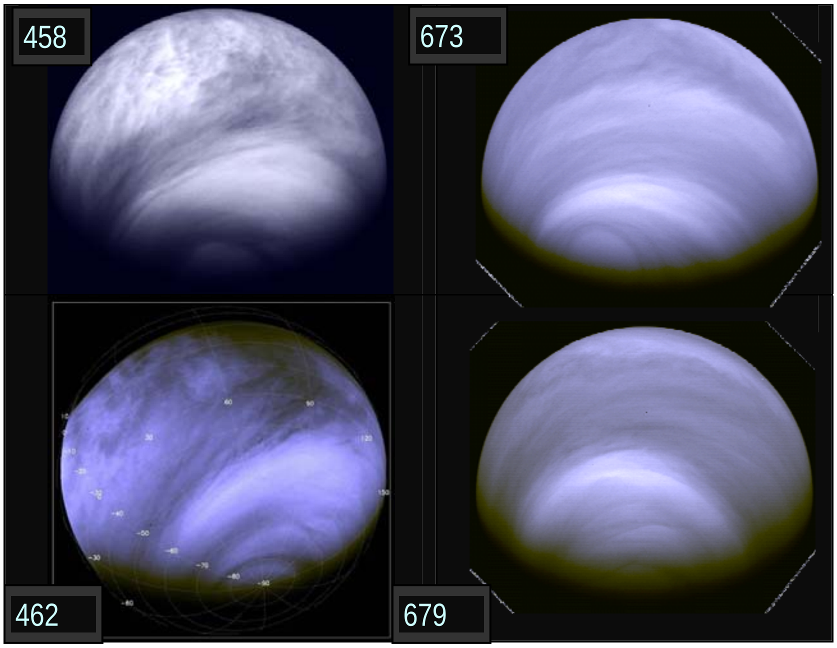

Venus viewed from Venus Monitoring Camera on Venus Express on orbits 458, 462, 673 and 679 indicating a sampling of cloud morphology variations over short periods. Why is it so variable?

APPENDIX

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